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This contract funded a three year study of wave particle interactions and substorm dynamics in the inner magnetosphere. We completed the first ground/satellite study of ion cyclotron waves generated near the plasmapause. We published several examples of waves observed simultaneously near the equator at L=4 by the DE 1 spacecraft and on the ground. In three cases correlation analysis yielded estimates of wave group delay between the equatorial source region and the ground. Model calculations that used measured plasma parameters agreed with the observational estimates. Among substorm related work, we extended an earlier study of pi2 signatures to lower latitudes to show that substorm onset signatures broaden in longitudinal extent with decreasing latitude. We showed that a pi2-based substorm detector would be a more reliable tool than one based on the AL index, and we developed and tested a simple pi2 index. The results showed that a more sophisticated pi2 index would result in

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WAVE PARTICLE INTERACTIONS IN THE INNER MAGNETOSPHERE

Final Report

Contents

I. Introduction

I. Introduction

This contract funded a three year study of wave particle interactions and substorm dynamics in the inner magnetosphere. Both of these phenomena are important causes of particle and energy transport in the magnetosphere. The main emphasis of our wave particle interaction study was electromagnetic ion cyclotron waves. These waves are an important mechanism by which energetic particles are lost from the inner and middle magnetosphere via precipitation into the atmosphere. The other problem we addressed, inner-magnetosphere substorm dynamics, is a primary cause of changes in spatial plasma distributions which in turn have major consequences on wave growth and the onset of instabilities which are one mechanism of energy transfer between the magnetosphere and ionosphere. The contract also funded the development of software tools for data management and wave analysis both to support the current analyses and for future use.

We completed the first ground/satellite study of ion cyclotron waves generated near the plasmapause. We published several examples of waves observed simultaneously near the equator at L=4 by the DE 1 spacecraft and on the ground. In three cases correlation analysis yielded estimates of wave group delay between the equatorial source region and the ground. Model calculations that used measured plasma parameters agreed with the observational estimates. Among substorm related work, we extended an earlier study of pi2 signatures to lower latitudes to show that substorm onset signatures broaden in longitudinal extent with decreasing latitude. We showed that a pi2-based substorm detector would be a more reliable tool than one based on the AL index, and we developed and tested a simple pi2 index. The results showed that a more sophisticated pi2 index would result in fewer false detections. We also formulated and began testing a new hypothesis on the triggering of substorms.

In the next section our scientific results and related efforts are summarised. Full descriptions of our scientific results are contained in the publications resulting from this contract. The final sections of this report provide lists of collaborating scientists, publications, and trips made, and as well as fiscal information.

II. Work Completed

A. Ion Cyclotron Waves: Ground Satellite Correlations

[Main references: Ludlow et al., 1989, 1990a]

We have made extensive use of data from the AFGL Magnetometer Network to study ion cyclotron waves generated in the Earth's inner magnetosphere. These waves are recorded on the ground as Pc1 pulsations, waves with periods of around 1 Hz, and so are best seen in the data from the search coil magnetometers. Waves of this type are often generated as the cold plasma refilling the plasmasphere interacts with the hot ions that were injected into the inner ring current during a magnetic storm or substorm so precipitating the ions.

Our efforts have been concentrated on correlating waves seen on the ground with spacecraft observations made near the magnetic equatorial region which is believed to be where these waves are generated. These waves tend to be guided along magnetic field lines in the magnetosphere, but when and if they reach the ionosphere they can propagate horizontally across field lines, in an ionospheric duct, to distant ground stations. We had two particular aims in this work, to study the propagation of these waves from the equatorial plane to the ground, so that ground-based data can be used to obtain meaningful statistics on the occurrence of these waves, and to search for waves generated near the plasmapause. It had long been inferred from ground data that waves must be generated here, but, owing to the lack of suitable spacecraft, few in situ spacecraft observations have been made in this region. We made use of the unusual orbit of DE 2 to search for waves near the plasmapause.

In an initial study we observed a Pc1 event simultaneously at the AFGL Magnetometer Network's Newport station (L=3, 1500 - 1600 MLT) and at GEOS 1 (L=7, 1230 - 1310 MLT) on August 8/9, 1977 between 2325 UT and 0015 UT. Throughout the event the satellite and ground station were separated by at least 2.4 hours in local time and 4 L-shells. At GEOS 1 the event had two frequency components, one just below and one just above the local He^+ gyrofrequency. During the first part of the event these components were narrow banded. In the later stages of the event the emissions observed in space were more broad band. The first part of the event was observed on the ground; the lower frequency component was present while the higher frequency component was detected only weakly. A comparision of wave spectra showed that the lower frequency component had the same frequency as a function of time in space and on the ground, but the temporal variations in the intensity and shape of the spectral peaks were different. Substorm onsets that occurred during the event were

apparent as Pi2 and PiB signatures in the ground-based search coil data. These onsets may have affected the reception of the signal at Newport. We concluded that the source region was localized both in longitude and L shell, and on the basis of this conclusion estimated the attenuation of the signal in the ionospheric duct to be 0.009 - 0.014 dB/km.

In a more extensive second study we presented results of the first ground-satellite correlation study of ion cyclotron wave events inside geosynchronous orbit. We found several intervals during which waves at the same frequency were observed simultaneously by the DE 1 GSFC Fluxgate Magnetometer and by the AFGL Magnetometer Network. This represented about 33% of the intervals during which waves were seen on the ground and DE 1 was in a favorable location (near the geomagnetic equator around L=4.6) to observe the wave generation region. Three of seven simultaneous events showed a positive correlation when a detailed correlation analysis was performed. The broadband nature of the other events prevented any detailed correlation analysis. Peaks in the cross correlation function occurred at delays of $30 - 100$ seconds and are interpreted as the group delay time of signals from space to the ground station. The small number of events seen in space during conjunction intervals results from the satellite's path missing the source region. When sources are missed by the satellite path they either exist at higher or lower L-shells and are ducted in the ionosphere to the Network (L=3); or they exist at the satellite L-shell but are missed due to their small spatial extent in local time.

B. Ion Cyclotron Waves: Theory and Modelling

[Main references: Ludlow, 1989; Ludlow et al., 1990b]

We complemented our observational study of electromagnetic ion cyclotron waves with a theoretical investigation of the growth and propagation of these waves.

Previous calculations of the wave growth rates had assumed that the wave vector aligned perfectly with the background magnetic field. This is a special case in which Landau damping of the waves by the thermal electrons can not occur. We generalized these earlier calculations and made linear growth rate calculations of electromagnetic ion cyclotron waves driven by hot anisotropic protons in a magnetized plasma in which the angle between the wave vector and the magnetic field was arbitrary. We chose model populations of O^+ and He^+ as well as H^+, with densities and temperatures typical of ion cyclotron wave generation regions inside the plasmasphere around L=3, and studied the behavior of growth regions in k-space. We found that although the growth rates peaked at $\theta = 0°$, they did not depend strongly on θ

for $\theta < 30°$. At large wave normal angles weak peaks in wave growth were found with much smaller growth rates than at 0°. Electron Landau damping of ion cyclotron waves maximized at very oblique wave normal angles where the growth rate was reduced significantly, but had little or no effect in the region of k-space ($\theta < 45°$) where the waves are growing the fastest.

In a second project we modelled the group delays of ion cyclotron waves from the equatorial region to the ground and compared them with the delays we had deduced from the DE 2/AFGL Magnetometer Network correlation study. We used plasma parameters measured by DE 2 as model inputs, and scaled these along dipolar field lines to compute the wave group velocity at each point along the field line. We then integrated these velocities to obtain a wave group delay. We did a parameter search to see how sensitive the delays were to the various model input parameters, and found that group delays are sensitive to cold plasma density variations of a few percent near the equator in the source region (which are hard to measure accurately). However, the group delays derived from this model were in good agreement with those deduced from the wave measurements.

C. Ion Cyclotron Waves: Analysis of Fine Structure

[Main reference: Hughes et al., 1989]

Al'pert and Fligel (1985, 1987) computed spectra of midlatitude pc1 emissions with much higher frequency resolution than had ever been done previously and discovered a number of new spectral features. They showed that the main spectral peak was flanked by 'satellite' peaks. One family of satellite peaks was separated from the central peak by frequencies of tens of millihertz, and placed symmetrically about the main peak. They argued that these peaks were caused by modulation of the signal at the resonant frequencies of the magnetospheric cavity. Other satellite peaks were irregularly spaced and of much lower intensity. They suggested that these peaks were the result of instabilities with minor parts of the energetic proton distribution. They also found peaks at twice and three times the frequency of the main peak that they believed were caused by non-linear plasma processes. Spectral features of this type could also be caused by non-linearities in the sensor or recording system or by features of the Fourier transform algorithm. For this reason we felt that these results should be checked using data from a different source and different analysis software.

We repeated the analysis of Al'pert and Fligel using data from the searchcoil magnetometers of the AFGL Magnetometer Network and an FFT analysis program which includes

careful preprocessing of the data. We selected long lasting pearl-type pulsations whose central frequency was constant with time and used data intervals long enough to provide 1 mHz frequency resolution. The temporal resolution of our data, 0.2 s, did not provide enough data points to make detailed spectra of single wave packets as was done by Al'pert and Fligel. Using 10 min data samples we found that the major spectral peaks did have 'satellite' peaks, in our case separated by typically about 8 mHz. Furthermore, the frequencies of these satellite peaks and their temporal evolution were identical at different recording stations. This indicates that the satellite peaks are a property of the source, not a propagation effect. However, the difference frequencies were related to the frequencies of peaks in a power spectrum made from the envelope of the wave-packet structure, so we concluded that the difference frequencies simply contain information on the shape and repetition frequency of the wave packets We found no evidence for second- or third-harmonic emissions, which suggests that these were caused by some nonlinearity in the Soviet recording or analysis system.

D. Magnetospheric Dynamics at Substorm Onset

[Main references: Singer et al., 1987; Cattell et al., 1987; Hughes, 1988; Lester et al., 1989]

The other major topic we have studied during the past three years has been the dynamics associated with magnetospheric substorms. The expansion phase onset of a magnetospheric substorm is accompanied by auroral brightenings, the development of field-aligned current systems, Pi2 magnetic pulsations, and particle injections and magnetic field changes at geosynchronous orbit. We have built on our earlier work which related onset signatures observed at midlatitudes (magnetic bays and Pi2 pulsations) to auroral signatures, to the location of the substorm currents (both the electrojet current and field aligned currents), and to signatures seen at geostationary orbit. By investigating the spatial and temporal relationship of these various signatures we believe we will gain insight into the complex plasma and particle dynamics associated with the substorm expansion phase.

We participated in a coordinated data analysis workshop (CDAW 8) devoted to substorm processes, that made a special study of certain substorms that occured in 1983 when ISEE 3 was in the deep tail and other spacecraft had fortunate conjunctions. This workshop provided an unusual opportunity to compare midlatitude and auroral signatures. One effort was concentrated on a comparison of the Pi2 pulsation polarization pattern observed by the AFGL Magnetometer Network, with global images of the aurora obtained by the DE 1

spacecraft. We studied a total of about eight events (not all of which were during CDAW 8 intervals) and found that, in general, the auroral brightenings occurred west of the central substorm meridian defined by the Pi2 polarization. Frequently several localized brightenings occurred, not all accompanied by Pi2 pulsations, but the low temporal resolution of the DE 1 images (images are 8 min apart) made it difficult to do precise timing. Some of these events merit deeper study.

Also as part of our CDAW 8 participation, we took part in a study, led by C.A. Cattell (UCB), that combined AFGL Magnetometer data, geosynchronous orbit magnetometer data and data from ISEE 1 and 2 located about 9 R_E down the tail on field lines that mapped to the active aurora observed by the DE 1 imager. Two Pi2 pulsation bursts were seen at all locations. In both instances very similar signatures were seen at both ISEE 1 and 2, 1500 km apart, implying an event scale size in excess of the spacecraft separation. The two events had entirely different signatures from each other in the spacecraft data, although similar signatures were seen on the ground. In one event signatures of several field-aligned currents were seen, as well as variable plasma flows, while in the second event, a single intense field-aligned current was seen at both ISEE and GOES 5, accompanied by a strong earthward plasma flow. Both events were associated with magnetic field compressions, and lasted about 5 minutes. Again, further work on this data set is warranted, and should provide some insight into the generation of Pi2 bursts.

In reviewing multisatellite field-aligned current observations, much of it our own work, we found that the signatures of the field-aligned current portion of the substorm current wedge, originally deduced from midlatitude magnetograms, is clear near geosynchronous orbit, provided the data is organized by the ground-based signature of the currents. But at geosynchronous orbit the magnetic perturbations exhibit far more fine structure, are often shorter-lived, and usually cover a smaller longitudinal extent than at midlatitudes. We concluded that all these observations suggest that the currents flow reasonably close to geosynchronous spacecraft, albeit on larger L shells. However too few observations have been made further down the tail to confirm whether the substorm current wedge pattern can be detected there.

In another study, we collaborated with Mark Lester (University of Leicester) to relate midlatitude observations of Pi2 pulsations to lower latitude observations. We found that inside the current wedge the longitudinal pattern of the Pi2 polarization azimuth observed at the low-latitude AFGL Magnetometer Network stations (40°N) agrees with the azimuth pattern observed at midlatitudes (55°N) without exception. However, outside the wedge

near the longitudes of the field-aligned currents, the azimuth does not change at low latitudes as it does at 55°N. The difference between the mid- and low-latitude observations was partially explained by the additional observation of positive H-component bays at the low-latitude stations, which suggested that the ground-based signature of the current wedge increases in longitudinal extent with decreasing latitude. We modelled the magnetic field perturbation caused by a substorm current wedge and these calculations agreeded with the observations. Another difference between mid and lower latitudes was that the sense of Pi2 polarization changed with latitude, but only west of the current wedge. Whereas the polarization is predominantly counterclockwise at all longitudes at midlatitudes, at low latitudes it is predominantly counterclockwise within and east of the wedge but predominantl clockwise west of the wedge. We found this latter observation hard to explain using any of the current theories of Pi2 pulsations.

E. Magnetospheric Substorm Triggers

[Main reference: Hughes and Kivelson, 1989; Kivelson and Hughes, 1990]

Many features of substorms are satisfactorily described by a phenomenological model in which the substorm onset is related to the formation of a neutral line within the plasma sheet close to the Earth. The substorm neutral line pinches off a portion of plasma sheet plasma and the substorm expansion phase is associated with the growth and tailward ejection of that plasma, called a plasmoid. This substorm model requires that the tail be stressed prior to the substorm onset and relates the development of tail stress to the input of energy from the solar wind, but the model does not specify the conditions required for the onset of the substorm expansion phase. In particular the model does not account for the fact that the amount of tail stress released in different substorms is highly varible and that the intensity of global substorm-related signatures can differ greatly.

We proposed an explanation for this variability in substorm intensity. We argued that the level of stress at which substorm expansion starts might be controlled by the tail field geometry. The field-line curvature required for the formation of a near-Earth neutral line is already present in the tail when the dipole axis is tilted towards or away from the sun. If substorms are most readily initiated when the dipole tilt is favorable, then the stress required to initiate a substorm would, on average, be smaller near the solstices, resulting in less intense substorms. For a given rate of energy input from the solar wind, maximum tail bending results in a larger number of smaller substorms. Geomagnetic activity, if measured

by a K-type index that records the largest disturbance in a 3-hour interval, will then be smaller. We argued that this mechanism provides a better explanation for those aspects of the semiannual and diurnal variations in geomagnetic activity that are independent of the IMF sector polarity. We also predicted that there should be annual and diurnal variations in the occurrence frequency and magnitude of substorms.

In order to test these last predictions we developed a computer algorithm that would recognise substorms in the AL index. Using this algorithm, we identified individual magnetospheric substorm signatures in a 6-year time series of the AL index, so generating a list of over 30,000 substorms. The substorms identified were parameterized by the onset time, duration and by a size estimate based on the integral under the AL curve. However the irregular distribution of the AL observatories made diurnal variations in substorm occurrence meaningless. We did find clear seasonal variations in both substorm occurrence frequency and size distribution, but these seemed to be controlled more by the irregular distribution of AE observatories, the offset of the dipole and spin axes and by the fact that all AE observatories are in the northern hemisphere, than by our proposed bent tail mechanism. We hope to further test our hypothesis if we can develop a more reliable substorm detector, our search for which is described in the next section.

F. Magnetospheric Substorm Detectors

[Main references: Singer and Hughes, 1988, 1989; Hughes and Singer, 1989]

The reliable detection of substorms is important both for scientific studies on the nature and causes of substorms and for the prediction and monitoring of geomagnetic disturbances in order to minimize their adverse effects. Excepting recourse to individual magnetograms and auroral records, the most reliable method of identifying substorms in past records is through the AL auroral index. This method has shortcomings. The AL index is time consuming to produce, so is rarely available until some years after the event, and the index suffers from a limited and uneven auroral zone coverage, which results in a fraction of substorms escaping detection. In an attempt to overcome these shortcomings, we began development of an index based on a midlatitude signature of substorm expansion phase onset, the Pi2 pulsation.

In an initial study that used one month of data from a single observatory we showed that the Pi2 index detected substorms missed by the AL index during both quiet times and moderately disturbed times. In a follow-up study we examined in detail data for July 1979, which we have used extensively in the past. We ran computer recognition programs over both

the Pi2 wave power index and over the AL index to obtain two separate lists of substorm identifications. A simple comparision of the two lists showed that many more "substorms" were detected by the Pi2 index. Then we examined time series plots of the midlatitude magnetogram data and looked in detail at the AL index and the chart showing the local time of the contributing station. From this study we concluded that the AL index misses over 50% of substorm onsets. Some of these are lost when the electrojet moves either too far poleward (during quiet times) or too far equatorward (during active times), and others are lost when enhanced convection near dawn results in a station near dawn contributing the AL value. The Pi2 identification we used resulted in too many false detections. However, a more sophisticated recognition algorithm could solve that problem. Routine detection of substorms using Pi2 pulsations would require fewer observatories than needed for AE, and in more accesssible locations. The Pi2 method certainly worked better during quiet times, but both methods failed more during particularly active times. An outstanding general problem is whether each Pi2, which often occurs in trains, really represents a true expansion phase onset. An answer to that can only come from further research into Pi2 pulsations and substorms.

G. Data Management and Analysis

An important part of our overall effort has been the development of data management and analysis software, not only for our own project, which is data-analysis intensive, but also as a general purpose tool that can be used by others. Our efforts can be divided into three interacting parts, a flexible data storage format that allows for easy access and retrieval, good data display programs that allow data to be displayed in a number of complementary ways, and a comprehensive suite of analysis programs that allow data, particularly time series data, to be analyzed in a number of ways.

Our data analysis and display software is based on a standard data storage format known as a flatfile. This is a flexible storage format that is nevertheless best suited to time series data of one sort or another.

We have spent a considerable amount of effort on improving our data display, and in making our programs easier to use, and better documented. We have concentrated on dynamic spectral displays of various parameters as these allow the display of large quantities of information in a small space. These techniques proved very useful in our studies of ion cyclotron waves, and should be useful in the analysis of data from the CRRES satellite. In

addition to these frequency/time displays, we have developed a full set of line-plot programs for plotting time series and spectra, making use of the graphics packages available at GL.

We have also developed and documented our package of analysis routines. All of our standard data manipulation and analysis procedures (data despiking routines, time-series filtering, FFT spectral and cross-spectral analysis, etc.) are incorporated into the flatfile data management and analysis package. We also developed new analysis procedures as the need arose in our scientific effort.

The flatfile analysis package we have developed is a powerful data analysis and display tool that can be used on any data that can be formatted into flatfiles, and will be especially useful for the analysis of data from the CRRES spacecraft.

In addition to this general purpose software, we have expended considerable effort in writting software for the routine display and analysis of CRRES data.

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III. BUSINESS DATA

A. Contributing Scientists

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C.A. Cattell (Univ. California, Berkeley)
H.L. Collin (Lockheed)
J.D. Craven (Univ. Iowa)
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D.P. Smits (Univ. Cape Town)
M. Sugiura (Kyoto Univ.)

B. Previous and Related Contracts

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F19628-84-K-0006	(12/1/83 - 2/28/87)
F19628-90-K-0003	(2/1/90 - 4/30/95)

C. Publications

i. Published Papers

W.J. Hughes, Multisatellite observations of field-aligned current systems, *Adv. Space Res.*, *8*, (9)321, 1988.

G.R. Ludlow, W.J. Hughes, N. Cornilleau-Wehrlin, and H.J. Singer, Simultaneous observation of a Pc1 pulsation by the AFGL Magnetometer Network and GEOS 1, *J. Geophys. Res.*, *94*, 6633, 1989.

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ii. Papers in Preparation

G.R. Ludlow, W.J. Hughes, and H.L. Collin, The ion cyclotron group delay for source regions near the plasmapause, to be submitted to *J. Geophys. Res.*

iii. Papers Presented at Meetings

G.R. Ludlow, Perpendicular Properties of the Growth of Ion Cyclotron Waves in the Magnetosphere, presented at the American Geophysical Union Spring Meeting, Baltimore, May 1987. Abstract: *EOS, Trans. Am. Geophys. Un.*, *68*, 386, 1987.

C.A. Cattell, D.N. Baker, W.J. Hughes, et al., CDAW-8 Observations of Pi2 Pulsations and Associated Substorm Processes on the Ground, presented at the American Geophysical Union Spring Meeting, Baltimore, May 1987. Abstract: *EOS, Trans. Am. Geophys. Un.*, *68*, 389, 1987.

H.J. Singer, W.J. Hughes, J.D. Craven, and L.A. Frank, DE-1 Auroral Images and Ground-based Magnetic Observations at Substorm Onset: CDAW-8, presented at the American Geophysical Union Spring Meeting, Baltimore, May 1987. Abstract: *EOS, Trans. Am. Geophys. Un., 68,* 389, 1987.

W.J. Hughes, Theory of Long Period Compressional Magnetospheric Waves, Invited Review Paper, IUGG XIX General Assembly, Vancouver, August 1987.

H.J. Singer, W.J. Hughes, J.D. Craven, and L.A. Frank, DE-1 Auroral images and ground-based magnetic observations at substorm onset: CDAW-8, IUGG XIX General Assembly, Vancouver, August 1987.

G.R. Ludlow, W.J. Hughes, and H.J. Singer, Observations of Pc1 events using ground-based and satellite measurements, IUGG XIX General Assembly, Vancouver, August 1987.

G.R. Ludlow, W.J. Hughes, N. Cornilleau-Wehrlin, H.J. Singer, and R.L. Arnoldy, Observations of Pc1 events using ground-based and satellite measurements, presented at the Chapman Conference on Plasma Waves and Instabilities in Planetary Magnetospheres and at Comets, Sendai, Japan, October 1987.

G.R. Ludlow, Perpendicular properties of the growth of ion cyclotron waves in the magnetosphere, presented at the Chapman Conference on Plasma Waves and Instabilities in Planetary Magnetospheres and at Comets, Sendai, Japan, October 1987.

G.R. Ludlow, W.J. Hughes, M.J. Engebretson, J.A. Slavin, M. Sigiura, and H.J. Singer, Ground-satellite Correlations of Pc 1 Events near the Plasmapause, presented at the American Geophysical Union Spring Meeting, Baltimore, May 1988. (Abstract: *EOS, 69,* 423, 1988)

G.R. Ludlow, W.J. Hughes, M.J. Engebretson, J.A. Slavin, M. Sigiura, and H.J. Singer, Pc 1 waves observed during conjunctions of DE 1 and the AFGL Magnetometer Network, presented at the American Geophysical Union Fall Meeting, San Francisco, December 1988. (Abstract: *EOS, 69,* 1385, 1988)

H.J. Singer and W.J. Hughes, Development of a Pi2 wave index for substorm detection and its comparison with the AL index, Presented at the American Geophysical Union Fall Meeting, San Francisco, December 1988. (Abstract: *EOS, 69,* 1382, 1988)

W.J. Hughes, G.R. Ludlow and H.J Singer, On the fine structure in the spectra of pc1 pulsations, presented at the AGU Spring Meeting, Baltimore, May 1989. (Abstract, *EOS, 70,* 452, 1989.)

M.G. Kivelson and W.J. Hughes, On the threshold for triggering substorms, presented at the AGU Spring Meeting, Baltimore, May 1989. (Abstract, *EOS, 70,* 445, 1989.)

G.R. Ludlow, W.J. Hughes, M.J. Engebretson, J.A. Slavin, M Sugiura, and H.J. Singer, Electromagnetic Ion Cyclotron Wave Study Using Dynamics Explorer 1 and the AFGL Magnetometer Network, presented at the 6th IAGA Scientific Assembly, Exeter, England, August 1989.

M.G. Kivelson, W.J. Hughes, and R.L. McPherron, Tail Hinging and Substorm Onset, presented at the 6th IAGA Scientific Assembly, Exeter, England, August 1989.

W.J. Hughes, and M.G. Kivelson, A Test of the Bent Tail Hypothesis of Substorm Triggering using the AL Index, presented at the 6th IAGA Scientific Assembly, Exeter, England, August 1989.

H.J. Singer, and W.J. Hughes, Comparisons between a Pi2 Wave Index and the AL Index for Substorm Detection, presented at the 6th IAGA Scientific Assembly, Exeter, England, August 1989.

G.R. Ludlow, W.J. Hughes, M.J. Engebretson, J.A. Slavin, M Sugiura, H.L. Collin, and H.J. Singer, Ground-Satellite Correlation Study of Ion Cyclotron Waves, presented at the AGU Fall Meeting, San Francisco, December 1989. (Abstract, *EOS, 70,* 1270, 1989.)

W.J. Hughes, and H.J. Singer, Substorm Detection using the AL Index and a Pi2 Power Index, presented at the AGU Fall Meeting, San Francisco, December 1989. (Abstract, *EOS, 70,* 1282, 1989.)

D. Travel

1987

In May, Professor Hughes and Dr. Ludlow traveled to Baltimore to attend the Spring American Geophysical Union Meeting where they both presented papers.

In August, Professor Hughes traveled to Vancouver, British Columbia, to attend the XIX General Assembly of IUGG. At the meeting he presented three papers describing research supported by this contract.

In October, Dr. Ludlow traveled to Sendai, Japan, to attend the Chapman Conference on Plasma Waves and Instabilities in Planetary Magnetospheres and at Comets. At the meeting he presented two papers describing research done under this contract.

In November, Dr. Mark Lester of Leicester University, England, visited Boston University to discuss research collaboration.

In December, Professor Hughes traveled to San Francisco to attend the Fall American Geophysical Union Meeting at which he presented a paper.

1988

In May, both Prof. Hughes and Dr. Ludlow traveled to Baltimore to attend the Spring American Geophysical Union Meeting where Dr. Ludlow presented a paper describing research performed under this contract.

In June/July, Prof. Hughes traveled to Helsinki, Finland to attend the XXVII COSPAR Meeting. He presented a review paper on field aligned currents prepared under this contract.

In December, Dr. Ludlow traveled to San Francisco to attend the AGU Fall Meeting where he presented a paper.

1989

In March, Dr. Ludlow traveled to NASA/Goddard SFC to attend a DE SWT meeting at which he described his research correlating DE 1 and AFGL Magnetometer Network data.

In April, Prof. Hughes attended the Chapman Conference on the Physics of Magnetic Flux Ropes held in Bermuda.

In May, Prof. Hughes attended the AGU Spring Meeting in Baltimore where he presented two papers describing work carried out under this contract.

In July/August, Prof. Hughes attended the IAGA 6th Scientific Assembly in Exeter, England, where he presented three papers describing work carried out under this contract.

In October, Prof. Hughes attended the Geospace Environment Modeling workshop at University of Maryland where he presented a review paper.

In December, Prof. Hughes and Dr. Ludlow attended the Fall American Geophysical Union Meeting in San Francisco where they each presented a paper describing work carried out under this contract.

1990

In May, Prof. Hughes attended the AGU Spring Meeting in Baltimore where he presented a paper.